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INVESTIGATION OF IMPACT RESPONSE FOR CFRP/STEEL HYBRID COMPOSITE PLATE UNDER LOW-VELOCITY IMPACT

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ABSTRACT

The response of composite plate embedded with steel wires subjected to low velocity impact was studied. The steel wires were embedded within the layers two and three of the composite laminate plates. The first order shear deformation theory (FSDT) as well as the Fourier series method was utilized to solve the governing equations analytically. A computer program was developed based on the analysis. The effect of volume fraction of steel on the deflections and in-plane strains and stresses on the composite plate under impact was studied. It was seemed that the embedding the steel wires within the layers of laminated composite plates would improve the impact resistance of the plate where, the transverse deflection of the center of the plate reduced from (1.68E-07 m) in the composite medium (the composite without steel wires) to (1.25E-07 m) in the hybrid composite plate in which the volume fraction of the steel is 9.3%.

KEYWORDS: The Steel, Plate Reduced, Hybrid Composite, Fraction

INTRODUCTION

Composite materials which are reinforced with fibers have many advantages due to their high specific strength and specific stiffness. This can be fabricated to optimize the strength and stiffness by changing fabrication parameters such as the stacking sequence and the number of plies of hybrid materials.

In many applications such as aircraft, automobiles industries and sport equipment the composite plates have been used. The dynamic response of composite structures subjected to dynamic loading has been studied in terms of analytical, numerical [1, 2] and experimental work [3, 4]. Theoretically, many researches have been developed for studying the behavior of composite structures under low velocity impact. The analytical model presented by Pierson and Vaziri [5] based on the combined effects of shear deformation, rotary inertia and the nonlinear Hertzian contact low with an aim of studying the low velocity impact response of simply supported laminated composite plates.

Embedding the Shape Memory Alloy (SMA) wires inside the traditional polymer composite can reinforce the damage tolerance of multilayered composite structure. This is because the existed SMA wires can generate recovery tensile stress inside the structure and hence reduce the deflection and the in-plane strains and stresses in transverse loading [6]. The effect of low velocity impact on the composite structures and prestressing of these structures was extensively studied in the past by Abrate[7], Olsson [8-9], and sun et al. [10] and many others. Birman et al. [11] also, demonstrate that if the SMA wires are embedded within the traditional polymer composite plates, tensile stress that results in heating of the wires increase the impact resistance of the structure.

The constitutive relationships are obtained following the method of Pates et al. [12] and Zhong et al. [13]. According to this method, micro mechanical relationships are obtained in two phases. First, these equations are

Obtained for a composite medium consisting of carbon fiber and matrix. Second, these relations are formulated for a composite medium treated as an orthotropic matrix with steel embedded within a medium.

In this paper, low velocity impact of symmetric cross ply composite plate is considered. Steel wires are embedded within layers in xx direction. The steel effect is employed to reduce transverse deflection of the plates and stresses.

Assumptions

Consider a cross-ply composite plate subjected to low velocity impact at the center. Steel wires are embedded within the layers two and three which result in ahybrid composite plate. The analysis is based on a number of assumptions that are listed below:

- Perfect bonding exists between layers.
- Low-velocity impact can be represented by a half sine function of time.
- The carbon, steel and matrix experience the same axial strain in the fiber direction and the same transverse stress in the plane perpendicular to the fiber.
- The first order shear deformation theory (FSDT) as well as the Fourier series was used to solve the governing equations analytically.

MICROMECHANICAL MODELS

The method employed to develop a micromechanics of steel hybrid composite is similar to that used by Pates et al. [12] and Zhong et al. [13]. According to this method, the properties of a composite medium that consists of ordinary fiber and matrix are evaluated first using an appropriate micromechanics then the addition of steel wires is considered using the same micromechanical model with composite medium treated as a transversely isotropic matrix. The formula for evaluation of the properties of a hybrid steel composite ply is listed in the APPENDIX.

Constitutive Equations

The plane stress constitutive equations for a lamina of constant thickness in the laminate coordinates are

$$\begin{Bmatrix}\sigma_x\\ \sigma_y\\ \tau_{xy}\end{Bmatrix} = \begin{bmatrix}\acute{Q}_{11} & \acute{Q}_{12} & \acute{Q}_{16}\\ \acute{Q}_{12} & \acute{Q}_{22} & \acute{Q}_{26}\\ \acute{Q}_{16} & \acute{Q}_{26} & \acute{Q}_{66}\end{bmatrix}\begin{Bmatrix}\epsilon_x\\ \epsilon_y\\ \gamma_{xy}\end{Bmatrix}$$

$$\begin{Bmatrix}\tau_{yz}\\ \tau_{xz}\end{Bmatrix} = \begin{bmatrix}\acute{Q}_{44} & \acute{Q}_{45}\\ \acute{Q}_{45} & \acute{Q}_{55}\end{bmatrix}\begin{Bmatrix}\gamma_{yz}\\ \gamma_{xz}\end{Bmatrix} \tag{1}$$

Where $\acute{Q}_{ij}$the transformed reduced stiffness matrix, $\{\sigma\}$and $\{\epsilon\}$ are the stresses and strains in laminate coordinates system respectively. Using integration of equation (1) through the thickness of the plate (h) yields

$$\left.\begin{matrix}\begin{Bmatrix}N\\ M\end{Bmatrix}=\begin{bmatrix}A_{ij} & B_{ij}\\ B_{ij} & D_{ij}\end{bmatrix}\begin{Bmatrix}\epsilon^o\\ k\end{Bmatrix} \text{ i, j=1, 2, 6}\\ \\ \{Q\}=\begin{bmatrix}k_{sh}^2 & A_{ij}\end{bmatrix}\{\gamma\}\text{i, j=4, 5}\end{matrix}\right] \tag{2}$$

Where, N and Q are a vector of forces and M is the vector of moments. A_{ij}, B_{ij}, and D_{ij} are the components of extensional and shear, coupling and bending stiffness matrices respectively. ϵ^o Andγ are the mid-plane and the shear strain respectively and k is the curvature. In addition, k_{sh} is the shear correction factor and is often taken to be (π^2/12).

Governing Equations

The assumed displacement field is [14].

$$\left.\begin{aligned} u(x,y,t) &= u^0(x,y,t) + z\psi_x(x,y,t) \\ v(x,y,t) &= v^0(x,y,t) + z\psi_y(x,y,t) \\ w &= w^o(x,y,t) \end{aligned}\right] \quad (3)$$

Whereu^0, v^0 and $w^o$are the plate displacement in x, y and z direction of the plate mid-plane and ψ_x and ψ_y are the shear rotation in the x and y direction.

Reducing the equations (2) to a simply supported symmetric cross ply laminated plate, ($B_{ij} = A_{16=}A_{26} = D_{16} = D_{26} = A_{45} = 0$). Also by neglecting the rotary inertia (I_3), results the following equations.

$$\left.\begin{aligned} & K_{sh}^2 A_{55}\left(\frac{\partial\psi_x}{\partial x} + \frac{\partial^2 w_o}{\partial x^2}\right) + K_{sh}^2 A_{44}\left(\frac{\partial\psi_y}{\partial y} + \frac{\partial^2 w_o}{\partial y^2}\right) + q(x,y,t) = I_1\ddot{w}_o \\ & D_{11}\frac{\partial^2\psi_x}{\partial x^2} + D_{12}\frac{\partial^2\psi_y}{\partial x\partial y} + D_{66}\left(\frac{\partial^2\psi_x}{\partial y^2} + \frac{\partial^2\psi_y}{\partial x\partial y}\right) - K_{sh}^2 A_{55}\left(\psi_x + \frac{\partial w_o}{\partial x}\right) = 0 \\ & D_{66}\left(\frac{\partial^2\psi_x}{\partial x\partial y} + \frac{\partial^2\psi_y}{\partial x^2}\right) + D_{12}\frac{\partial^2\psi_x}{\partial x\partial y} + D_{22}\frac{\partial^2\psi_y}{\partial y^2} - K_{sh}^2 A_{44}\left(\psi_y + \frac{\partial w_o}{\partial y}\right) = 0 \end{aligned}\right] \quad (4)$$

Where

$$\left.\begin{aligned} (A_{ij}, B_{ij}, D_{ij}) &= \int_{-h/2}^{h/2} Q_{ij}(1, z, z^2)\, dz \\ (\rho, I_1, I_3) &= \int_{-\frac{h}{2}}^{\frac{h}{2}} \rho_o\,(1, 1, z^2) dz \end{aligned}\right] \quad (5)$$

Where ρ represent the density of the plate, ρ_o the density of each layer, h is the thickness of the plate, $Q_{ij}$for i,j=1, 2, 6 are the reduced in-plane stiffness matrix components and Q_{ij} for i,j=4,5 are the reduced transverse shear stiffness matrix components.

The work was focused upon a simply supported rectangular plate with dimensions, length (a) width(b) and with the boundary conditions:

$w_0 = \psi_{y=0}$at$x$=0, a also $w_o = \psi_x = 0$at y=0, b

ANALYSIS OF THE RESPONSE

The analysis of response (stress, strain and displacement) is based on the expansion of force, displacement and rotation in a double Fourier series, each expression is assumed to separately consisting of position and function of time, therefore, the above boundary condition are satisfied the following expressions (Navier solution).

$$\left.\begin{aligned} w_o(\mathrm{x,y,t}) &= \textstyle\sum_{n=1}^{\infty}\sum_{m=1}^{\infty} W_{mn}(\mathrm{t}) \sin \alpha x \cos \beta y \\ \psi_x(\mathrm{x,y,t}) &= \textstyle\sum_{n=1}^{\infty}\sum_{m=1}^{\infty} X_{mn}(\mathrm{t}) \cos \alpha x \sin \beta y \\ \psi_y(\mathrm{x,y,t}) &= \textstyle\sum_{n=1}^{\infty}\sum_{m=1}^{\infty} Y_{mn}(\mathrm{t}) \sin \alpha x \cos \beta y \end{aligned}\right] \tag{6}$$

Where, the U_{mn}, V_{mn}, W_{mn}, X_{mn} and Y_{mn} are the time dependent coefficient to be determined and $\alpha = m\pi\ /\ a$ and $\beta = n\pi\ /\ b$

In the case of concentrated force $F(t)$ applied at the location (x, y) the forcing function is equal to [15-16]

$$q(x,y,t) = \textstyle\sum_m \sum_n p_{mn}(t) \sin(m\pi/a)\, x \sin\,(n\pi/b) \tag{7}$$

$p_{mn}(t)$ are the terms of the Fourier series. It is clear that the maximum deflection is encountered if the impact occurs at the center of the plate where $(x = x_c = a/2)$ and $(\ y = y_c = b\ /\ 2)$. Therefore, the largest deflection and stress will be occurred also at the same location. For a concentrated force located at the point

$$(x_c, y_c)^{[17]} p_{mn}(t) = (4F(t)/ab).\sin\left(\frac{m\pi}{a}\right) x_c.\sin\,(\frac{n\pi}{b}) y_c \tag{8}$$

Where $F(t)$ is the impact force and can be represented [18]

$$\left.\begin{aligned} F(t) &= p\sin(\pi t/t_o) \text{For} 0 < t \le t_o \\ F(t) &= 0 \text{For} t > t_o \end{aligned}\right] \tag{9}$$

Where to is the impact duration and $p$its amplitude.

Using equation (6) the system of equations (4) can be reduced to the following system of ordinary decouple differential equations.

$$\begin{bmatrix} m_{11} & 0 & 0 \\ 0 & m_{22} & 0 \\ 0 & 0 & m_{33} \end{bmatrix} \begin{Bmatrix} \ddot{W}_{mn} \\ \ddot{X}_{mn} \\ \ddot{Y}_{mn} \end{Bmatrix} + \begin{bmatrix} k_{11} & k_{12} & k_{13} \\ k_{21} & k_{22} & k_{23} \\ k_{31} & k_{32} & k_{33} \end{bmatrix} = \begin{Bmatrix} p_{mn}(t) \\ 0 \\ 0 \end{Bmatrix} \tag{10}$$

Where, the parameters of the above equation are defined as follow

$$m_{11} = m_{22} = m_{33=I_1}, k_{11} = k_{sh}^2\left(A_{55}d_{xx} + A_{44}d_{yy}\right), k_{12} = k_{sh}^2 A_{55} d_x\ , k_{13} = k_{sh}^2 A_{44} d_y$$

$$k_{21} = k_{12}\ , k_{22} = k_{sh}^2 A_{55} + (D_{11}d_{xx} + D_{66}d_{yy})\ , k_{23} = (D_{12} + D_{66}) d_x d_y$$

$$k_{31} = k_{13}\ , k_{32} = k_{23}, k_{33} = k_{sh}^2 A_{44} + (D_{66}d_{xx}\ + D_{22}d_{yy})$$

Based on the analytical model and using matlab software, can calculate the parameters W_{mn}, X_{mn} and Y_{mn} and by substituting these values into (6), the values ofw_o , ψ_x, ψ_y would be calculated. Using [19]:

$$\epsilon_x = z.\psi_{x,x}, \epsilon_y = z.\psi_{y,y}\, , \gamma_{xy} = z.\left(\psi_{x,y} + \psi_{y,x}\right), \tag{11}$$

NUMERICAL CALCULATIONS AND DISCUSSIONS

By using the computer program for the following numerical example can illustrate the effectiveness of the steel wires in limiting a damage inflicted by low-velocity impact where, the effect of embedding the steel on dynamic response of composite plate under impact is studied and discussed. Asymmetric cross-ply simply supported for all edges rectangular

plates made of carbon fiber-polyester with different volume fraction of steel and with a lamination of [0° 90° 90°0°] was considered. The size of the plate is 24 cm × 24 cm × 0.6 cm. The impact characteristics are $p = 300\ N$, t_o=300 μs and volume fraction (v_s) of steel was taken equal to (0%, 2.25%, 3.25%, 9.3%). The plate materials considered in this work as mentioned were carbon fiber/ polyester with the following properties.

- **Carbon Fiber**

  $E_1 = 230\ GPa, E_2 = E_3 = 15\ GPa, G_{12} = 27\ GPa, G_{23} = G_{13} = 7\ GPa, \nu_{12} = 0.2, \rho = 1790\ Kg / m^3$

- **Polyester**

  $E = 3\ GPa, G = 1.6\ GPa, \nu = 0.35, \rho = 1100\ Kg / m^3$

  And the steel wires of (0.7 mm) diameter had the following properties

  $E = 193\ GPa, G = 77\ GPa, \nu = 0.27, \rho = 8000\ Kg / m^3$

The accuracy of present analytical and used program was verified by a comparison of deflection-time relationship obtained from this solution with those obtained using a finite element solution of [18]. In this comparison the volume fraction of the steel was taken to be zero. The steel wires were placed along the x-direction, which corresponds to the 90° fiber orientation in composite medium and only in the layers 2 and 3.

Figure 1 shows the maximum value of deflection (w) decreases from (1.68E-07) in the composite medium (the composite without steel wires, curve 1) to (1.25E-07) in the hybrid steel composite plate in which the steel have the volume fraction of 9.3%, curve 4. Thus, 26% reduction is occurred.

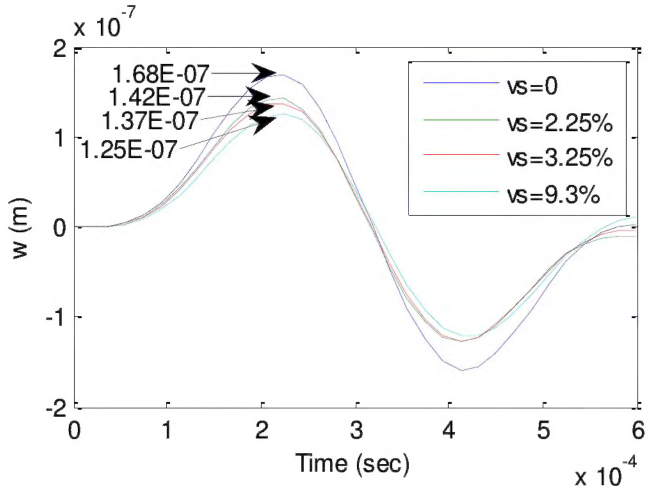

Figure 1: Effect of Steel Volume Fraction on Deflection History

The reduction of both the xx and yy direction of the in-plane strains and stresses during the impact are remarkable where, maximum stress and strain reduced by 8%, 4%, 28% and 28% for stress xx, stress yy,strain xx and strain yy respectively in the composite plates to hybrid composite plates. Figures 2, 3, 4 and 5 demonstrate the variation of the in-plane strains and stresses with time.

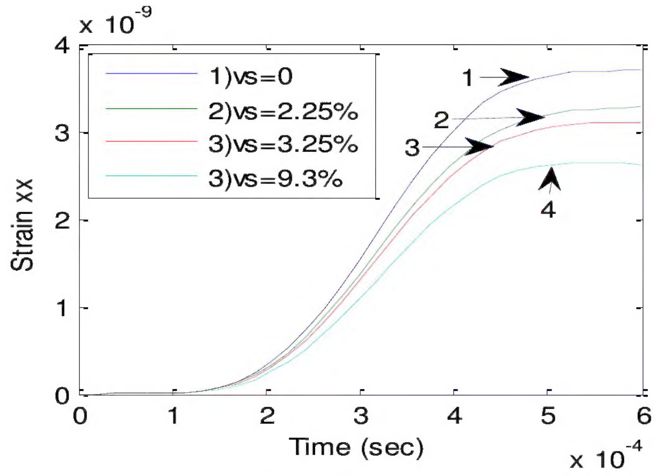

Figure 2: Variation of Strain xx with Time

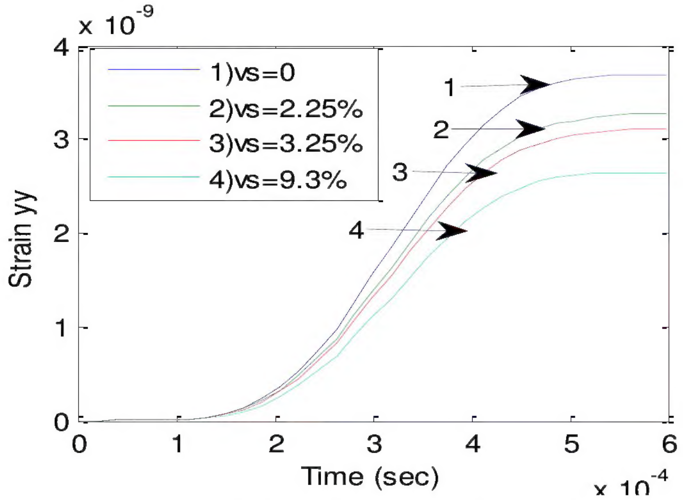

Figure 3: Variation of Strain yy with Time

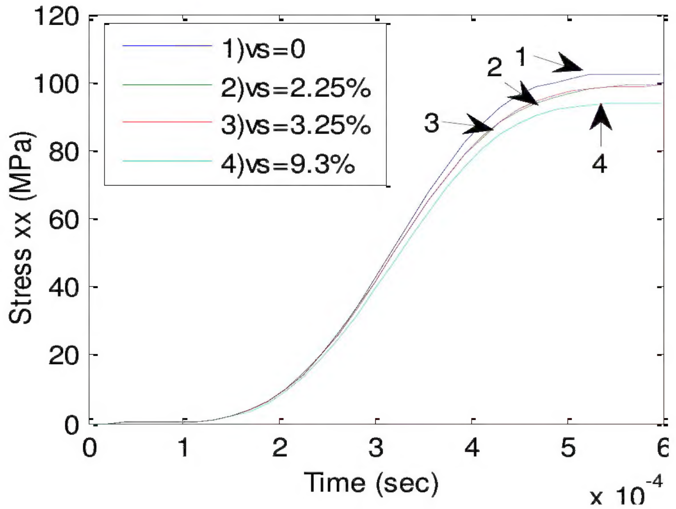

Figure 4: Variation of Stress xx with Time

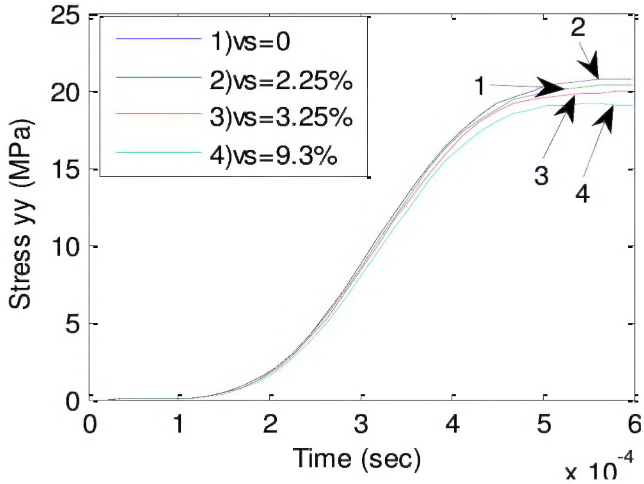

Figure 5: Variation of Stress yy with Time

CONCLUSIONS

The impact response of the low impact velocity upon hybrid steel composite plate is studied using simultaneously the first order shear deformation theory (FSDT) and Fourier series to solve the governing equations analytically. A computer program based on the analytical model and using the matlab software was utilized. The program is capable to compote the following parameters:

- Deflection history of the composite plate
- In-plane strains and stresses history of the composite plate

The results obtained from this program also indicated that the embedding the steel wires within the layers of carbon fiber-epoxy laminated composite plate results in that the deflection and in-plane strains and stresses of the plate decrease with the increasing the volume fraction of steel. Furthermore, the effectiveness of steel wires can be further improved by optimizing their distribution through-out the plate.

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APPENDICES

Micromechanics of steel hybrid ply

Properties of a composite medium consisting of transver selyiso tropic carbon fiber and an isometric matrix

$$E_1^c = E_m v_m + E_{1f} v_f \ , \ E_2^c = \frac{E_m}{[1-\sqrt{v_f}\left(1-\frac{E_m}{E_{2f}}\right)]}, \ G_{12}^c = \frac{G_m}{[1-\sqrt{v_f}\left(1-\frac{G_m}{G_{12f}}\right)]} \ , \ \nu_{12}^c = \nu_m v_m + \nu_f v_f$$

Properties of a hybrid steel ply

$$E_1^h = E_1^c v_c + E_s v_s \text{ , } E_2^h = \frac{E_2^c}{[1-\sqrt{v_s}\left(1-\frac{E_2^c}{E_s}\right)]} \text{ , } G_{12}^h = \frac{G_{12}^c}{[1-\sqrt{v_f}\left(1-\frac{G_{12}^c}{G_s}\right)]} \text{ , } \nu_{12}^h = \nu_{12}^c v_c + \nu_s v_s$$

In these equations, the superscript, 'c' identifies the composite medium (fiber and matrix), and 'h' identifies the hybrid medium (composite medium and steel), while the subscripts 'm' and 'f' refer to the matrix and the fibers, respectively. The subscript '1' and '2' refer to the longitudinal along the (fibers) and transverse directions respectively. Other notations are as follow:

E= modulus of elasticity, G=shear modulus, ν=ppoison's ratio, v= volume fraction, where the subscript 's' identifies the steel.